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## **Bridging the gap: $^{40}\text{Ar}/^{39}\text{Ar}$ dating of volcanic eruptions from the ‘Age of Discovery’**

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### **ABSTRACT**

Many volcanoes worldwide still have poorly resolved eruption histories, with the date of the last eruption often undetermined. One such example is Ascension Island, where the timing of the last eruption, and consequently, the activity status of the volcano, is unclear. Here, we use the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating technique to resolve ages of the three youngest lava flows on the island, which are hawaiites and mugearite with 1.5 – 1.9 wt%  $\text{K}_2\text{O}$ . In dating these lavas, we provide the first evidence of Holocene volcanic activity on Ascension ( $0.51 \pm 0.18\text{ka}$ ;  $0.55 \pm 0.12\text{ ka}$ ;  $1.64 \pm 0.37\text{ ka}$ ), determining that it should be classed as an active volcanic system. In addition, we demonstrate that the  $^{40}\text{Ar}/^{39}\text{Ar}$  method can reproducibly date mafic lava flows younger than 1 ka, decreasing the gap between recorded history and geological dating. These results offer new prospects for determining patterns of late-Holocene volcanic activity; critical for accurate volcanic hazard assessment.

### **INTRODUCTION**

Globally, >11% of humans live within 100km of a volcano that has been active within the past 10,000 years (Small and Naumann, 2001; Siebert et al., 2015). This geographical association of people with active volcanoes means it is critical to develop methods to

elucidate complete volcanic eruptive histories. Understanding the timing and character of the most recent volcanic activity is not only important for interpreting magmatic processes, it is key to volcanic hazard assessment and to anticipating likely impacts of future eruptions. However, of the 1325 terrestrial volcanoes that erupted during the Holocene (Global Volcanism Program, <https://volcano.si.edu>; Venzke, 2013), 534 currently have unknown ages for their most recent eruptions (Fig. DR1 and Table DR4 in the GSA Data Repository<sup>1</sup>). Volcanic settings typically have wide-ranging styles of volcanic activity, with varying consequences for populations and infrastructure in their proximity (Wilkinson et al., 2016), so verifying the timing of recent activity is essential for long-term contingency planning (Marzocchi and Bebbington, 2012). Understanding eruptive time-style relationships is often hampered by the sparseness of verifiable eye-witness accounts of eruptions, or by the limitations of geological dating techniques for late-Holocene volcanic materials. In sparsely vegetated areas such as Ascension Island, the prospects for  $^{14}\text{C}$  dating are limited, and lava flows are challenging to date except by direct radiometric techniques, such as  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology. Previously, the  $^{40}\text{Ar}/^{39}\text{Ar}$  approach has been applied to date volcanic rocks as young as 1–2 ka using sanidine phenocrysts (e.g., Renne et al., 1997; Yang et al., 2014). However, the dating of Holocene basaltic groundmass is more challenging (e.g., Jicha, 2009; Wijbrans et al., 2011; Hicks et al., 2012) (Fig. 1) owing to low concentrations of radiogenic argon ( $^{40}\text{Ar}^*$ ) relative to contamination from atmospheric argon ( $^{40}\text{Ar}_{\text{ATM}}$ ). Here we report  $^{40}\text{Ar}/^{39}\text{Ar}$  ages that have been obtained for mafic lava flows on Ascension Island erupted at <1 ka, which determine that Ascension is volcanically young and should be classed as an ‘active’ volcano. To the best of our knowledge, the ages are the youngest reproducible  $^{40}\text{Ar}/^{39}\text{Ar}$  ages that have ever been acquired with the technique and they coincide with the increase of chronicled observations of travel associated with the early modern European ‘Age of Discovery’ (early 15th to 17th centuries). These data demonstrate that  $^{40}\text{Ar}/^{39}\text{Ar}$  dating can be employed to bridge the gap between these historical accounts and the geological record.

## ASCENSION ISLAND

Ascension Island (7°56’S, 14°22’W) is an ocean island volcano located in the South Atlantic Ocean, ~90 km west of the Mid-Atlantic Ridge axis. It is a British Overseas Territory with a current population of ~800. In terms of the composition and style of volcanic activity, it serves as an archetype of ocean island systems. The volcanic rocks define a transitional, to mildly alkaline, basalt→hawaiite→mugearite→benmoreite→trachyte→rhyolite sequence that spans a wide range of eruptive styles. The central and eastern sectors of the ~ 98 km<sup>2</sup>

island are predominantly composed of trachyte and rhyolite pyroclastic deposits, lava flows, and domes. The northern, southern, and western regions comprise mafic lava flows punctuated by scoria cones (e.g., Weaver et al., 1996). Ascension is speculated to have ‘credible evidence’ as an ‘active’ volcanic system based on the fact it has volcanic features with a ‘youthful appearance’ (Global Volcanism Program; Venzke, 2013), where an ‘active’ system is defined as one proven to have erupted during the Holocene (Siebert et al., 2015). Scholarship from the past 100 years records the presence of geomorphologically young lava flows, which preserve original flow surface features, no soil development, and host little or no vegetation (Daly, 1925; Atkins et al., 1964). Based on these field observations, some authors have hypothesized that the last eruption may have been within the past 1 k.y. (Daly, 1925; Packer, 1983). However, there are no data proving Ascension has erupted within the past 10 k.y., and recent  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of Ascension lavas (Jicha et al., 2013) does not date any deposit younger than  $38 \pm 9$  ka. Previously uninhabited Ascension Island was first sighted in A.D. 1501 (De Gray Birch, 1875), during the European ‘Age of Discovery’. This period was characterized by extensive overseas exploration, driven by the search for natural resources, new trade routes (Fig. 2A), and new territories to rule (Studnicki-Gizbert, 2007), with details of exploration recorded and published for readership across Europe. Prior to colonization in 1815, Ascension was used as a stopping place for ships to take on provisions. Despite the fact that sailors who recorded visits frequently explored the island, there are no direct observations of eruptive activity, although references are made to residual fumarolic activity and the recent nature of volcanic activity (D’Aprés de Manneville et al., 1816; Temple and Anstey, 1936) (see the Data Repository for historical documentation). As no records describe a directly observed eruption, we infer that the last eruption of Ascension likely occurred before historical documentation. Currently, there are no specific volcanic risk management plans in place on Ascension Island, despite the island housing important military and communications-related infrastructure. With fresh-looking lava flows but no historical accounts of eruptions, and Pleistocene  $^{40}\text{Ar}/^{39}\text{Ar}$  ages, the activity status of the island and, hence, volcanic risk, is unclear.

## **METHODS AND SAMPLING**

The youngest volcanic deposits on Ascension Island, based on stratigraphy (Nielson and Sibbett, 1996) and appearance (surface morphology, no soil development or vegetation) are mafic lava flows outcropping in the north and northwest of the island, in close proximity to infrastructure. As part of a larger  $^{40}\text{Ar}/^{39}\text{Ar}$  dating campaign, three of these flows, namely

South Sisters flow (sample AI14–412), Comfortless Cove flow (sample AI14–414), and the Davidson flow (sample AI15–625), were targeted to determine the age of the most recent eruption on Ascension (Figs. 2B and 3; see the Data Repository). The South Sisters and Davidson flows erupted from the Sisters Peak scoria cone complex, whereas the Comfortless Cove flow issued from a previously unmapped vent near the northwest coast of the island (Figs. 2B and 3). These flows are ‘a‘ā lava flows that traveled distances of ~1.7–3 km from their source, during eruptions associated with mild explosive activity and scoria production. The South Sisters and the Davidson flows are hawaiites, whereas the Comfortless Cove lava is mugearite. Whole rock K<sub>2</sub>O values range from 1.5 to 1.9 wt% (Table DR1). For each sample aliquot, 100 mg of phenocryst-free groundmass were CO<sub>2</sub> laser stepheated, and the Ar-isotope ratios were measured using an ARGUS V multi-collector noble gas mass spectrometer (Mark et al., 2009) (the spectrometer has undergone a series of upgrades and changes in measurement protocol; full details are provided in the Data Repository). Background and air calibrations were run following every measurement step during incremental heating experiments in order to provide careful control on background corrections and mass spectrometer discrimination. Measurement duration times were increased in order to maximize measurement precision (see the Data Repository). For such young materials, it is critical to not make an assumption concerning the trapped <sup>40</sup>Ar/<sup>36</sup>Ar component, and as such, avoid the use of age spectra, which yield ‘model’ ages calculated using the modern-day atmospheric <sup>40</sup>Ar/<sup>36</sup>Ar and the uncertainty of this measurement (Lee et al., 2006; Mark et al., 2011). We used the inverse isochron approach (e.g., Renne et al., 1997) and allow these data to define an initial trapped component and age.

## RESULTS

<sup>40</sup>Ar/<sup>39</sup>Ar data (Table DR2), when displayed on isotope correlation plots (Fig. 4), exhibit shallow, statistically significant, inverse isochrones (metric: sum of squares; probability cutoff: 0.05). The initial <sup>40</sup>Ar/<sup>36</sup>Ar derived from the y-intercept is analytically indistinguishable from the modern-day atmospheric <sup>40</sup>Ar/<sup>36</sup>Ar ratio (Lee et al., 2006; Mark et al., 2011), and data define a mixing line with the ingrown radiogenic <sup>39</sup>Ar/<sup>40</sup>Ar component (x-intercept). The mean square of weighted deviates (MSWD) ranges from 0.49 to 1.1 for all samples, consistent with MSWDs for our data population sizes (Wendt and Carl, 1991), and p values are all >0.05, supporting the data having age significance. Isochrons define ages of  $0.51 \pm 0.18$  ka for South Sisters flow,  $0.55 \pm 0.12$  ka for Comfortless Cove flow, and  $1.64 \pm 0.37$  ka for the Davidson flow. Given the difficulty of dating such young material using the

$^{40}\text{Ar}/^{39}\text{Ar}$  approach, these data have relatively large age uncertainties owing to the extrapolation of data from close to the y-intercept (initial  $^{36}\text{Ar}/^{40}\text{Ar}$  trapped component) to the x-intercept ( $^{39}\text{Ar}/^{40}\text{Ar}$ ) (Table DR2; Fig. 4). These ages are temporally coherent with the inference from the historical data that the most recent activity closely preceded the beginning of the historical record.

## DISCUSSION

For a comprehensive understanding of potential for future activity at a volcanic center, it is important to characterize both the timing and style of recent volcanism. The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages presented here provide the first definitive evidence that Ascension Island has erupted within the Holocene, and it is therefore classed an ‘active’ volcanic system. The most recent activity at Ascension comprised mafic lava flows with mild explosive activity, and it is envisaged that any future volcanic hazards may include lava flows, ballistics, tephra fall, and gas emissions. In order to produce the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages presented here, which to the best of our knowledge are the youngest published reproducible ages produced by this technique, we increased measurement durations and ran background and air calibrations following every measurement. However, we attribute much of the success of being able to attain ages so young to the sample quality and preparation. Full details are contained within the Data Repository, but, in short, groundmass was fresh and dense, and particular attention was paid to the elimination of all phenocryst-rich or altered fragments in our samples. Comparison of the mildly alkaline lavas in this study with ocean island basalts worldwide (Humphreys and Niu, 2009) shows the Ascension lavas are comparable in terms of  $\text{K}_2\text{O}$  content. The mean  $\text{K}_{72}$  value ( $\text{K}_2\text{O}$  wt% corrected for fractionation to Mg# 72) for Ascension mafic lavas is  $1.36 \pm 0.57$  (1 s.d.), and is within one standard deviation from the global mean  $\text{K}_{72}$  value of  $1.12 \pm 0.64$  (total range 0.01–4.62). Therefore, there is potential for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating to be successfully applied to many more Holocene ocean island lavas. Worldwide, 30% of sub-aerial Holocene oceanic intraplate and rift volcanoes have unknown dates for the last eruption (see the Data Repository). In these settings, complete Holocene eruptive histories are currently confounded by limited historical records, the frequent lack of material suitable for  $^{14}\text{C}$  dating, and the difficulty in dating young Holocene rocks using  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. For example, 40% of oceanic intraplate and rift zone volcanoes are situated on islands that have written records dating back <500 years (Fig. 1; Table DR3), limiting the time frame of eye-witness accounts of past eruptions. The results of this study offer new prospects for dating young ocean islands, as well as volcanism in other tectonic settings. This could not only

enhance understanding of volcanic evolution and magmatism, but considerably improve future hazard assessments.

## CONCLUSIONS

New  $^{40}\text{Ar}/^{39}\text{Ar}$  ages presented here ( $0.51 \pm 0.18$  ka;  $0.55 \pm 0.12$  ka;  $1.64 \pm 0.37$  ka) show that the gap between radioisotopic dating methods and historical accounts can be bridged. It is fair to anticipate that technological developments and technique refinement will continue to advance, with a subsequent improvement in measurement precision for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of young materials. Ages for young lava flows will markedly improve our knowledge of volcanic activity by providing temporal data for recent eruptions, a critical component for reliable volcanic hazard assessment.

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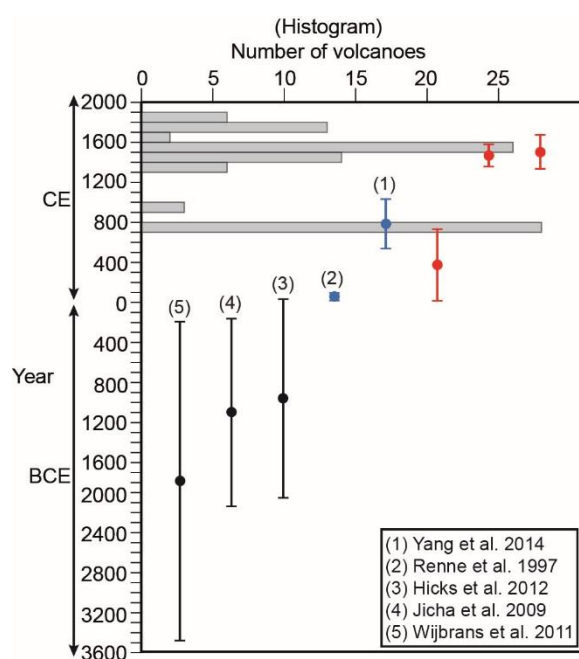
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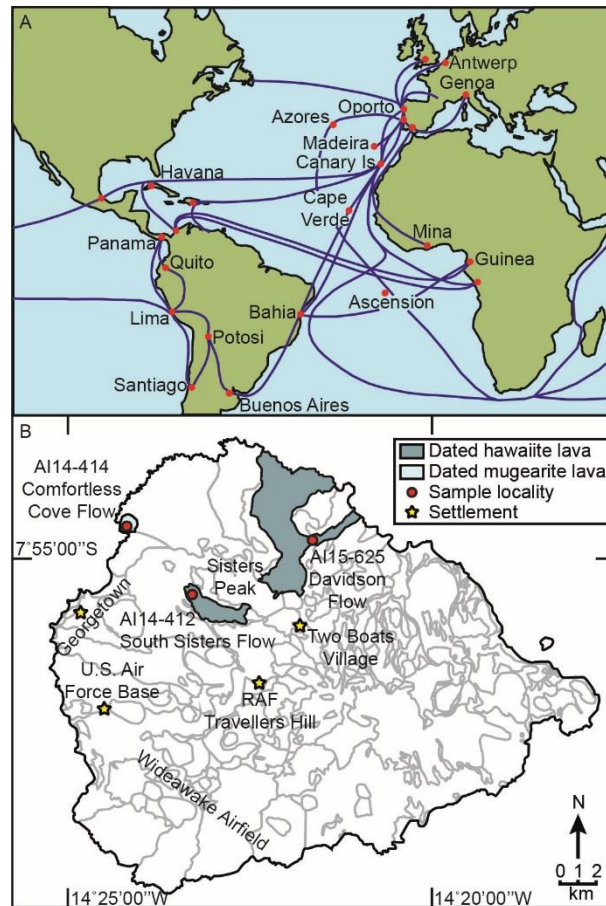
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## FIGURE CAPTIONS

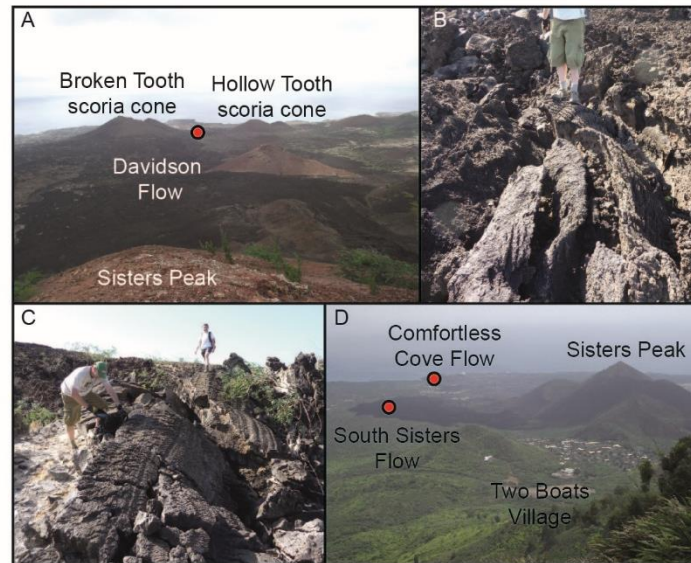


**Figure 1.** Histogram of the date of first verifiable written record or discovery of islands with Holocene oceanic intraplate and rift zone volcanoes, worldwide, overlain by  $^{40}\text{Ar}/^{39}\text{Ar}$  Ar ages from this study (red circles), previous young  $^{40}\text{Ar}/^{39}\text{Ar}$  Ar ages determined using sanidine phenocrysts (blue circles), and mafic groundmass (black circles). See Table DR3 (see footnote 1) for historical data and references. Note: all  $^{40}\text{Ar}/^{39}\text{Ar}$  Ar ages within this text are

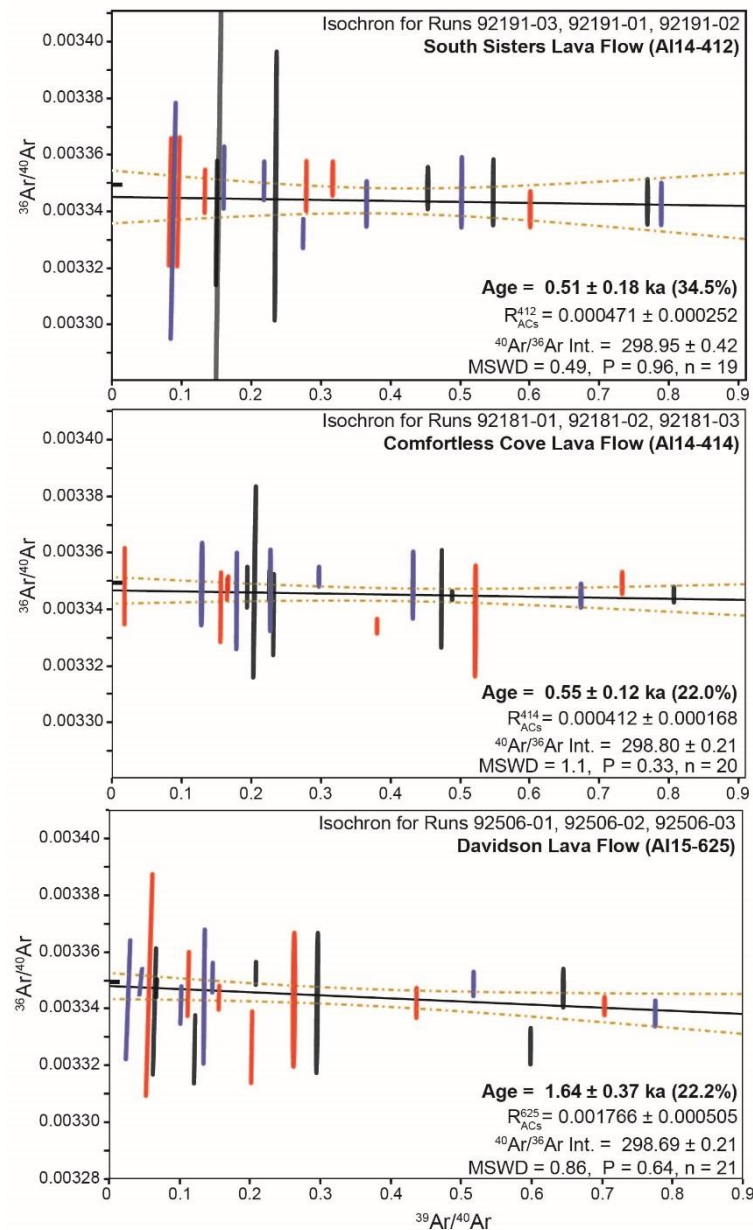
reported/ re-calculated as  $\pm 1\sigma$  full external uncertainty relative to the optimization model of Renne et al. (2010) using the parameters of Renne et al. (2011) and the Alder Creek sanidine (ACs) age of  $1.1891 \pm 0.0008$  Ma (Niespolo et al., 2017).



**Figure 2.** A: Location of Ascension Island in the South Atlantic Ocean, and Portuguese trade routes (modified from Studnicki-Gizbert, 2007). B: Geological map of Ascension, adapted from Weaver et al. (1996) and Nielson and Sibbett (1996), with sample locations.



**Figure 3.** Photographs of dated lava flows, Ascension Island. A: Davidson lava flow seen from Sisters Peak. B: Surface morphology of South Sisters flow. C: Surface morphology of Comfortless Cove flow. D: Sisters Peak scoria cone complex with South Sisters and Comfortless Cove lava flows.



**Figure 4.** Isotope correlation plots. For each individual lava flow, three aliquots per sample were dated, color-coded black, red, and blue (Table DR2 [see footnote 1]). Plots show the total data collected for each individual flow. Isochron-defined ages with associated R-values (sample-standard intercalibration factors, Renne et al., 1998) are shown. MSWD—mean square of weighted deviates; Int.—intercept.

<sup>1</sup> GSA Data Repository item 2018393, detailed methods, raw isotope and XRF data, historical records, Figures DR1 and DR2, and Tables DR1– DR4, is available online at <http://www.geosociety.org/datarepository/2018/>, or on request from [editing@geosociety.org](mailto:editing@geosociety.org).